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Scaling of plant roots for geotechnical centrifuge tests using juvenile live roots or 3D printed analogues

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ABSTRACT: Geotechnical centrifuge modelling of vegetated slopes requires appropriately scaled plant roots. Recent studies have independently suggested that juvenile live plants or 3D printing to fabricate root analogues could potentially produce representative prototype model root systems. This paper presents a critical comparison of juvenile versus 3D printed approaches in terms of their representation of root mechanical properties, root morphology and distribution of the additional shear strength generated by the roots with depth. For the 3D printing technique, Acrylonitrile Butadiene Styrene (ABS) plastic material was used, while for live plants, three species (Willow, Gorse and Festulolium grass), corresponding to distinct plant group functional types (tree, shrub and grass), were considered. The tensile strength and Young's modulus of the 'roots' were collected from uniaxial tension tests and shear strength data of rooted soil samples was collected in direct shear. The prototype root characteristics as modelled were then compared with published results for field grown species and the benefits and challenges of using these two modelling approaches is discussed. Finally, some recommendations on realistically modelling plant root systems in centrifuge tests are given.

1 INTRODUCTION

Vegetation as a low-cost, carbon-neutral natural alternative to conventional ground reinforcement techniques, has been recognised in geotechnical and ecological engineering practice to prevent shallow landslides and erosion (Stokes et al., 2009, 2014). However, they are rarely incorporated explicitly within geotechnical design, principally due to perceived issues of unpredictability in location and variability in biomechanical properties of the roots and hydrological properties of the soil-root composite.

The University of Dundee has had a long-running collaboration with the James Hutton Institute on this issue and has provided some new insights into the design and implementation of projects to mitigate slope instability. These include element scale investigation into root mechanical and hydrological effects (e.g. Mickovski et al., 2009; Loades et al., 2010, 2013; Boldrin et al., 2017a, b; Leung et al., 2017), large-scale investigation into the global slope performance and detection of the failure mechanism of vegetated slopes under rainfall or earthquakes using either centrifuge modelling or numerical modelling approaches (e.g. Sonnenberg et al., 2010, 2011; Liang et al., 2015, 2017a; Liang and Knappett, 2017a), development of analytical models for predicting the deformation response of vegetated slopes (Liang and Knappett,

2017b), and development of rapid in situ testing technique for determining rooted soil properties (Meijer et al., 2016, 2017).

Among these studies, geotechnical centrifuge modelling can provide relatively low cost testing while maintaining a high level of fidelity. It can be used to investigate the global performance of vegetated slopes under known boundary conditions and identify deformation and failure mechanisms of vegetated slopes through image analysis techniques such as particle image velocimetry (PIV) (White et al., 2003). However, in using a geotechnical centrifuge to investigate in detail the engineering performance of vegetated slopes, correct scaling of plant root systems is a substantial challenge (Liang et al., 2017b).

Recent studies have independently shown that using juvenile plants or 3D printing techniques could potentially produce prototype root systems that are highly representative of corresponding mature root systems both in terms of root mechanical properties and root morphology. These methods offer different advantages as an approach for scaling root systems. For example, 3D printed root analogues have good repeatability of architecture and mechanical properties and can be easily and quickly produced. Live plants, on the other hand, can provide highly representative root-soil interaction properties and also more correct stress-strain response. However, many challenges and uncertainties still exist for the use of both types of model roots.

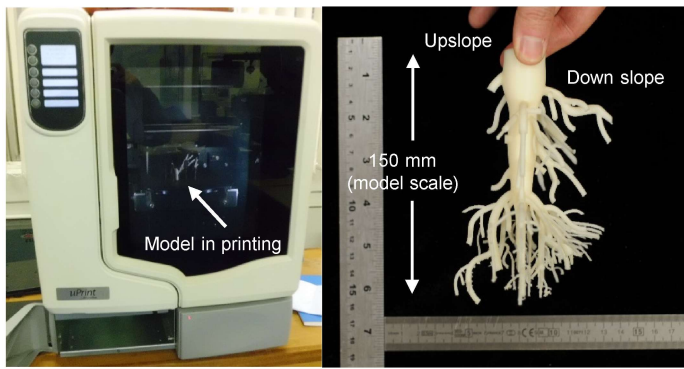


Fig.1 1:10 geometrically-scaled ABS plastic root model from 3D printer

The aim of this paper is to compare these two types of modelling approaches in terms of their representation of root mechanical properties, root morphology and distribution of the additional shear strength generated by the roots with depth based on databases collected at the University of Dundee. Insights and recommendation are made based on these comparisons for better selection of root analogues that may be applied to a wider range of practical problems.

2 ROOT MODEL

2.1 3D printed root analogues

The root analogues discussed in this paper are a 1:10 geometrically-scaled tree root cluster consisting of a tap-root system (see Fig.1), the root architecture used as a template was based on the tap-root system of a white oak tree located at the Warnell School for Forestry and Natural Resources, University of Georgia (Danjon *et al.*, 2008). The root analogue was fabricated using a Stratesys Inc. uPrint SE ABS rapid prototyper (known more commonly as a 3D printer) following the procedures outlined in Liang *et al.* (2014). Further details relating to the design and fabrication process for this model can be found in Liang *et al.* (2017a).

2.2 Juvenile live plants

The juvenile live plants discussed in this paper represent 1:15 geometrically-scaled model roots. Three species, *Salix viminalis* (Willow, variety Tora), *Ulex europaeus* L.(Gorse) and *Lolium perenne* × *Festuca pratensis* hybrid (Festulolium grass), which correspond to distinct plant functional groups (tree, shrub and grass, respectively) with contrasting root systems were selected following a preliminary assessment of suitable species for use in slope engineering applications.

These were cultivated for approximately two or three months (two month for Willow and Festulolium grass, three months for Gorse, due to slower growth)

in 150 mm diameter tubes under controlled lighting and temperature (16 h daylight per day under controlled temperature of 27.25 ± 0.38 °C (Mean± SE), and 8 h night per day at a temperature of 22.15 ± 0.13 °C) . Water was supplied every two days using a watering can. The amount of water supply was decided on the basis of maintaining soil field capacity (5 kPa suction), which corresponds with a gravimetric water content of 0.25 gg^{-1} .

The resulting root systems obtained from growth are shown in Fig.2. After the desired growing time, the three species developed significantly different root morphologies. Festulolium grass had a typical fibrous root system (Fig.2 b); Gorse had a tap root system that consisted of a thick tap root with numerous secondary roots less than 0.5 mm in diameter were attached (Fig.2 c); and Willow developed a root system with numerous branches of different diameters (Fig.2 a).

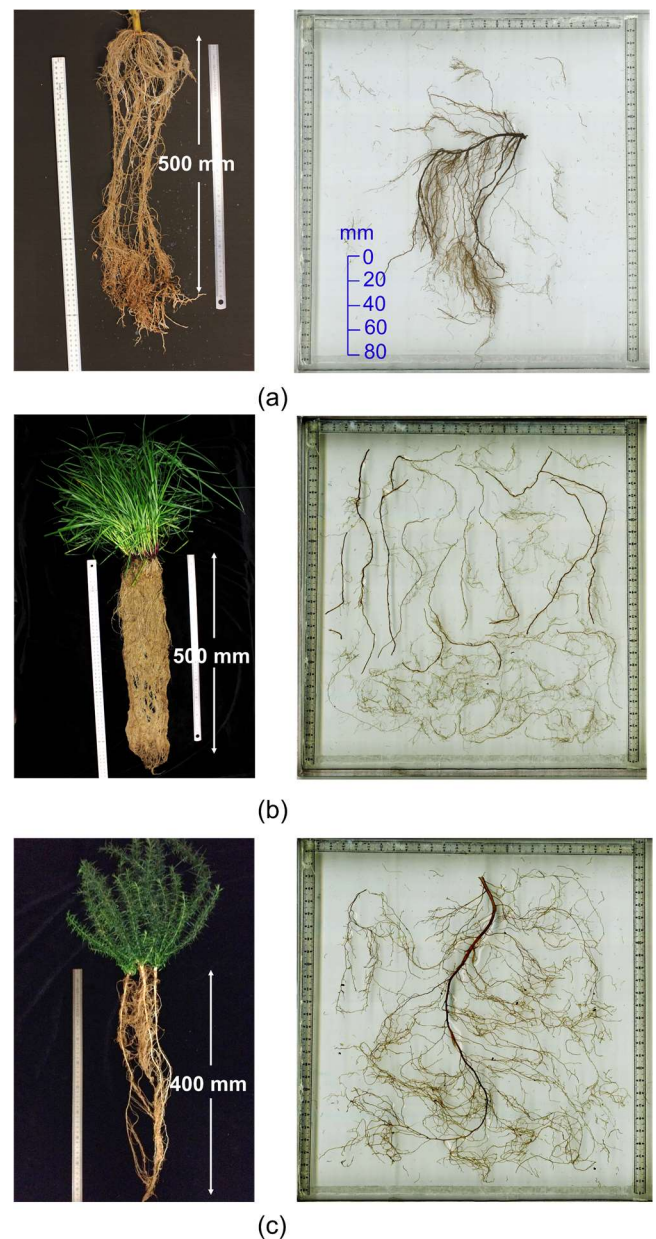


Fig.2 The model juvenile live plants used in this study, showing maximum rooting depth and scanned root architecture (at model scale) : (a) Willow; (b) Festulolium grass; (c) Gorse

Table 1. Scaling laws for centrifuge testing related to this study (After Taylor, 2003; Muir Wood, 2003)

Parameter	Scaling law: Model/Prototype	Dimensions*
Root diameter	1/N	L
Rooting depth	1/N	L
Tensile Strength	1	M/LT ²
Shear strength	1	M/LT ²
Young's Modulus	1	M/LT ²

* L = length; M = mass; T = time.

3 METHDOLOGY

Here only a brief description of how the parameters were obtained will be presented and full details about the testing setup can be found in Liang et al. (2017a,b) for 3D printed root analogues and juvenile live plants, respectively.

The biomechanical properties (specifically, strength and stiffness) of model roots were determined from uniaxial tensile tests and three-point bending tests. The shear strength of rooted and fallow samples were obtained from a custom-designed large direct shear apparatus (Liang et al., 2015; Mickovski et al., 2009). The additional shear strength provided by roots was taken as the maximum difference in shear resistance between the rooted and fallow soil samples divided by the 'working' shear plane area (e.g. Zone of Rapid Taper (ZRT), Danjon and Reubens, 2008). The centrifuge scaling laws related to this paper are shown in Table 1.

4 RESLUTS AND DISCUSSION

4.1 Bio-mechanical properties of roots

The measured values (Mean \pm SE) of tensile strength and Young's Modulus for 3D printed root analogues and juvenile live plants within different diameter ranges were scaled up according to centrifuge scaling laws (see Table 1) and plotted against the upper and lower bounds of mature root data collated from the literature (Fig.3). Specifically, data for tensile strength of mature field roots were collected from 40 species of trees, 12 species of shrubs and 21 species of grasses/herbs (see Mao et al., 2012). While data Young's Modulus of mature field roots were collected from 6 species of trees, 5 species of shrubs and 2 species of grasses/herbs (Operstein and Frydman, 2000; Van Beek et al., 2005; Mickovski et al., 2009; Fan and Su, 2008; Teerawattanasuk et al., 2014).

Compared with juvenile live plants, 3D printed ABS root analogues are stronger and stiffer in terms of modelling root biomechanical properties. However, it is still a great improvement compared with previous analogue materials (e.g. wood) used in previous studies. It should be noted that the mechanical properties for the 3D printed root analogues shown in Fig.3 were

collected from straight rod samples with individual layering of material aligned parallel to the axis of the root analogue. This scenario may represent an ultimate material mechanical condition. However, when a root cluster with complicated root morphology is printed (like shown in Fig.1), individual fibres within one root segment will not always be aligned to be parallel to the root axis for each root. As a result, the mean values of tensile strength and Young's Modulus within different diameter ranges in a complex 3D architecture are expected to be lower than the ones shown, as obtained from uniaxial tensile tests or three/four points bending tests. To identify such assumptions, further material characterisation tests are required on cylindrical samples with individual layers aligned in different directions relative to the root axis.

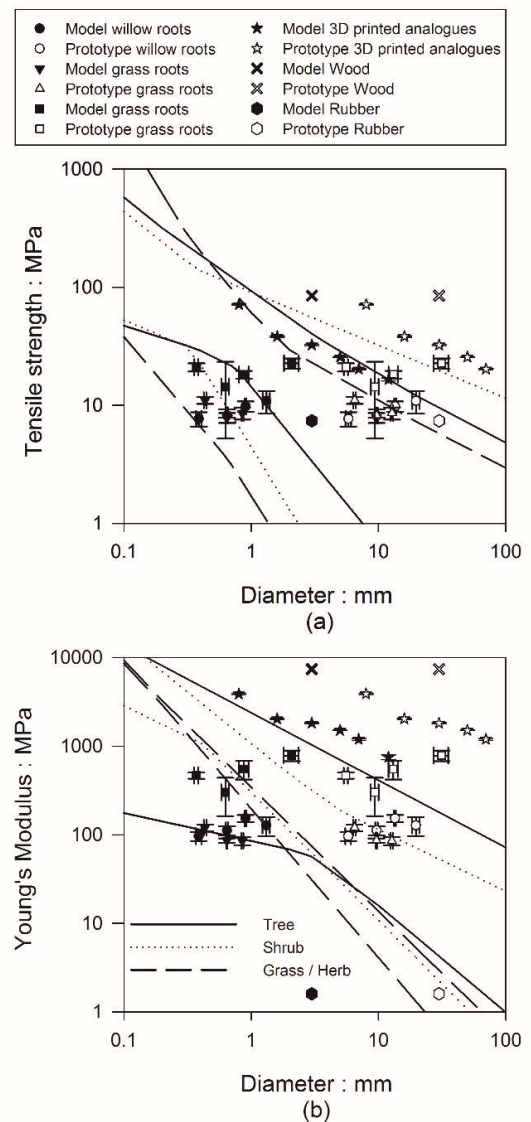


Fig.3 Comparison of root biomechanical properties between model roots (juvenile live plants (Mean \pm SE) and root analogues) and mature plants collected from the literature (Root tensile strength data, n=40, 12 and 21 for trees, shrubs and grasses/herbs, respectively; Root Young's Modulus data, n = 6, 5 and 2 for trees, shrubs and grasses/herbs, respectively): (a) Tensile strength; (b) Young's Modulus

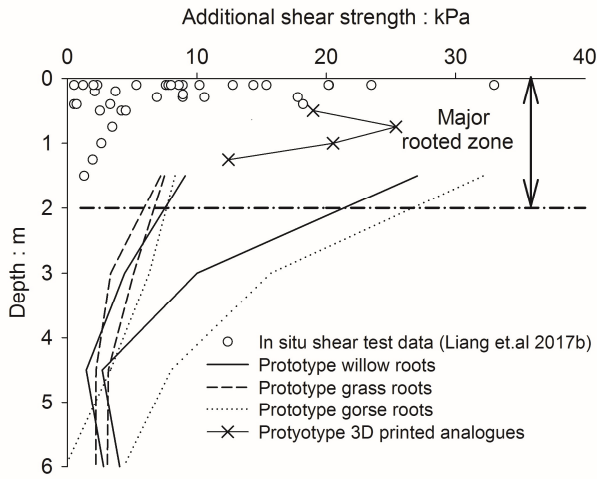


Fig.4 Comparison between the increased shear strength provided by the juvenile plants and 3D printed ABS plastic root analogues at prototype scale and root reinforcement data collected from the literature

However, such a potential lowering of strength has been indirectly observed in terms of a lower overall additional shear strength provided by roots through a comparison of the 3D root cluster in Fig.1 and a group of straight rods with aligned layers having the same root distribution across a certain shear plane; further details can be found in Liang et al (2017a).

4.2 Root morphology

Through attentive selection of plant species and growing time, use of live plants in the centrifuge can potentially simulate many types of root morphology in the field. This is also true of 3D printing. However, it should be noted here that, both the 3D printing technique and juvenile live plants approach have a certain threshold of root diameter which can be modelled. For example, the minimum root diameter within the uPrint printer is 0.75 mm (Liang et al., 2017a); as a result, a large amount of very fine or fine roots will not be included in prototype root models. For juvenile plants, the minimum root diameter observed was less than 0.1 mm. Such a drawback should be given particular attention when modelling vegetated slope problems in which fine roots play a major role on root mechanical effect, such as for grassed areas. It is possible that the fine material in the 3D printed case could be simulated by the addition of a quantity of fibres surrounding the ABS model.

4.3 Shear strength of root-reinforced soil

The shear strength measured for 3D printed root analogues and juvenile live plants in the direct shear apparatus is compared in Fig.4 to root contributions from large in-situ shear box tests conducted for some common species collected from field from a database collated by Liang et al. (2017b). It should be noted

here that the shear tests conducted on juvenile live plants could not consider the variation of soil confining stress due to the limitations of the testing apparatus. As a result, the original measured values, only represented the lower bound values (as shown in Fig.4) considering the effect of soil confining stress on the shear strength increase of rooted soil (Duckett, 2013; Liang et al., 2017a). The upper bound values of root contribution to soil shear strength for juvenile live plants shown in Fig.4 was derived using Wu and Waldron's model (WWM, Wu et al., 1979) through assuming all roots were mobilized and broken simultaneously as Waldron (1977) did:

$$c_r = 1.15 \times T_r \times RAR \quad \text{Eq.1}$$

Where c_r is additional shear strength provided by roots, T_r is average tensile strength, and RAR represents root density across each shear plane, defined as the ratio between root cross sectional area and the 'working' cross-sectional area of shear plane (e.g. ZRT). It should be noted here that the derived upper bound values represent the ultimate shear strength root can provide, and the actual root contributions are generally than such values (e.g. Pollen and Simon, 2005; Docker and Hubble, 2008; Bischetti et al., 2009; Loades et al., 2010; Mao et al., 2012).

Fig.4 clearly demonstrates that in situ direct shear tests on field plants were generally performed on very shallow shear planes (less than 0.2 m deep) due to the limitations of available shear apparatus, which highlights the benefit of using the centrifuge modelling approach for vegetated slope problems, where much more representative stresses can be simulated. It should also be noted that due to the large size of test apparatus required, field tests considered only small elements of rooted soil, while the scaled tests were able to test the root system for a complete plant or tree. It is not surprising therefore that the model systems generally provide higher amounts of reinforcement compared to the field, as the root systems are able to redistribute stresses internally via their interconnected architecture. In terms of the magnitude of root reinforcement, both 3D printed root analogues and juvenile live plants could provide a reasonable magnitude of rooted strength within the major rooted zone (down to 2 m below ground level) compared with the values reported in the literature for direct in situ shear tests, which generally between 2 – 20 kPa (Norris et al., 2008; Bischetti et al., 2009).

However, compared with the successful control of rooting depth for printed root analogues, the prototype rooting depth of live plants (even for such a short growing period) reached deep within the soil (to 6 m in Fig.4), leading to a different slope response compared with the field conditions, where roots are mainly concentrated in the top 2 m of soil (Jackson et al., 1996). However, as indicated by Liang et al (2017b), although juvenile live plants penetrated

deeper than the field conditions at prototype scale, the main effective contributions of roots to soil strength are still located in the shallow layer. The reason for this is because the root contribution in the deeper soil layers (>3m) are relatively small (less than 30%) compare with the fallow soil strength at the same depth. In other words, using juvenile plant roots to scale root reinforcement under field conditions may not be perfect, but it still can provide a representative and informative mechanical model, including the major root reinforcement at the surface and strongly reducing shear strength with increasing depth.

5 FUTURE INSIGHT

Using juvenile plants or 3D printing technique as reported in this paper is currently limited to use in modelling root mechanical reinforcement, and hydrological effects (chiefly transpiration) have not been taken into consideration. Some trials, which combine both mechanical root reinforcement and evapotranspiration have been reported by Ng et al. (2014, 2016).

The idea of applying external suction through a vacuum system on live poles (Ng et al., 2016) or high air-entry value (AEV) porous filters which are made of cellulose acetate (Ng et al., 2014) appears to be effective in modelling water uptake behaviour. Unfortunately, these models are currently based on very simple root geometry, mainly straight rods, occasionally with some highly simplified branching patterns. Considering the influence of root morphology on root mechanical reinforcement (e.g. Ghestem et al., 2014) and root water uptake (e.g. Boldrin et al., 2017a), such a model may not provide a reliable simulation of slope response.

However, the concept of using external suction to simulate root water uptake behaviour may be combined with the 3D printing technique through fabricating hollow root analogues with more realistic root morphology. In terms of fabricating a porous structure, 3D printing can easily achieve this, however, finding a printable material with a high air entry value is a challenge.

In contrast with this, whether live plants can still maintain evapotranspiration behaviour during enhanced gravity is still uncertain. Even if this was possible, the time scaling is likely to mean that it would be difficult to model water uptake representatively at prototype scale.

6 SUMMARY AND CONCLUSIONS

This paper presented a critical comparison of juvenile live plants versus 3D printed root analogues in terms of their representation of root mechanical properties, root morphology and distribution of the additional shear strength generated by the roots with depth. The

results suggest that both approaches are imperfect but can still provide a representative and informative mechanical model. Specifically, juvenile plants provide more representative root mechanical properties, and also more correct stress-strain response, including the maximum strain and stress localisation. They are also ideal for use in tests where the ground conditions would prohibit placement of a 3D printed model (e.g. in compacted or cohesive soils). However, these properties are biologically variable and so this method may not be ideal for cases when multiple centrifuge tests must be compared which are to have the same rooted soil properties.

In contrast with this, 3D printed analogues have much better control in modelling the distribution of the additional shear strength generated by the roots with depth, even though the analogues are stiffer than live roots. Combined with their repeatability, this approach is better suited to testing programmes where comparative tests must be undertaken with directly comparable rooting conditions (e.g. when slope height or loading conditions are variables) in granular media.

Further developments that can more realistically model coupled root mechanical and hydrological effects are required.

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